10/031239
PCT/GB01/02293
PTO/PCT Rec'd 17 JAN 2002

IMPROVEMENTS TO FILTERS

The present invention relates to a filter comprising plural thin film bulk acoustic resonators (FBARs) and more particularly, is directed to a piezoelectric filter which is manufactured using thin film technology in order to obtain a low close-in rejection and a low out-of-band rejection at high frequency.

Thin film bulk acoustic resonators (FBARs) are attractive devices since they show resonant peaks at high frequency, particularly in the MHz and GHz regions. Moreover, FBARs can be achieved in a small device size (~mm). Thus they are considered to be useful not only as resonators, but to be applied for filters, transducers, etc., which would be installed in small, light, thin electric appliance products, such as a mobile phone.

It is known that an electric filter can be made with plural FBARs. That kind of filter can work in MHz frequency region or in GHz frequency region. Generally speaking, for a band-pass filter, the rejection level compared to signal-pass area improves when more FBARs are used for the filter.

Figure 9 shows one example of a filter comprising four FBARs. The four FBARs are separated into 2 groups according to their functions in the filter. FBAR1 and FBAR2 in Figure 9 are connected in series. Therefore they are in one group. Also, FBAR3 and FBAR4 are connected in parallel and in the other group. Usually those FBARs are prepared on one substrate and prepared under the same procedure. Therefore each FBAR consists of exactly the same structure. In other words, the same thickness and the same materials for all layers on each FBAR. And also, usually each FBAR has the same working area size.

It is important to prepare a band-pass filter at high frequency in the MHz or GHz region because those frequency regions are often used for wireless communications these days. For a band-pass filter, it is extremely important that both the close-in rejection and the out-of-band rejection are low. Therefore, a technique has been demanded to make a filter with a good close-in and out-of-band rejection.

An object of the present invention is to prepare a filter, showing a low close-in rejection and a low out-of-band rejection which comprises plural FBARs. By this invention, these properties can be obtained by changing the sizes of the working areas between FBARs in series and in parallel.

The filter comprises a plurality of FBARs in which at least one FBAR is in series and one FBAR in parallel.

Each FBAR comprises a plurality of layers consisting of (from lower to upper): a substrate, a dielectric layer, one or more metal layers acting as a lower electrode, a piezoelectric layer, one or more metal layers acting as an upper electrode.

An FBAR exhibits a series resonance and a parallel resonance at respective frequencies that are functions of the thicknesses of all of the layers. In such a filter, it is useful to alter the sizes of the working areas between the FBARs in series and the FBARs in parallel.

The working area is usually restricted with the area sizes of electrodes in contact with the piezoelectric layer to form the FBARs. In this case, the resonant peaks are exhibited as different shapes of the reactance curves for FBARs in series relative to FBAR's in parallel.

As a result of making a filter using FBARs in series and in parallel with different working areas, a filter which shows a low close-in rejection and a low out-of-band rejection can be obtained.

The theory is described using Figure 9. In Figure 9, if all FBARs are prepared under the same condition, both FBARs in series (FBARs 1 and 2) and FBARs in parallel (FBARs 3 and 4) exhibit exactly the same resonant peaks. Then, if the thickness of the piezoelectric layer is changed for FBARs in series relative to FBARs in parallel, the resonant peaks appear at a different frequency but the shape of the resonant peaks is the same, as shown in Figure 10(a). As a result of making a filter using those FBARs which comprise a different thickness of the piezoelectric layer for FBARs in series relative to FBARs in parallel, a through signal (S_{21}) of the filter is obtained, as shown in Figure 10(b). In Figure 10(b), close-in rejections appear at frequencies of f_{s2} and f_{p1} and an out-of-band rejection is at a frequency region below f_{s2} and above f_{p1}.

On the other hand, if in Figure 9, it is assumed that the size of the top electrode and bottom electrode on FBARs in series (FBARs 1 and 2) and on FBARs in parallel (FBARs 3 and 4) are different but the other dimensions on all FBARs are supposed to be the same as the filter in Figure 10, then FBARs in series and FBARs in parallel show different shapes of reactance curves, as shown in Figure 11(a). In Figure 11(a), the shapes of the curves are different because of the differences between the capacitances of the working areas. As a result of preparing a filter using those different FBARs in series and in parallel, a filter which shows a low close-in rejection, particularly at f_{s2}, and a low out-of-band rejection can be obtained, as shown in Figure 11(b).

In order to alter the sizes of electrodes, one example would be to change the mask designs for the electrodes for the FBARs in series relative to the FBARs in parallel.

The invention will now be described in more detail, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 illustrates a schematic diagram of a preferred filter which comprises three FBARs in series and three FBARs in parallel.

Figure 2 illustrates a top view and a cross section view of a FBAR.

Figure 3 illustrates the S parameters of a FBAR which comprises electrodes whose size is 110 microns square and a piezoelectric layer whose thickness is 1.2 microns, and which is used as FBARs in series on a preferred filter.

Figure 4 illustrates S parameters of a FBAR which comprises electrodes whose size is 285 microns square and a piezoelectric layer whose thickness is 1.255 microns, and which is used as FBARs in parallel on a preferred filter.

Figure 5 illustrates a S_{21} curve of a preferred filter which comprises three similar FBARs in series, comprising electrodes whose size is 110 microns square and a piezoelectric layer whose thickness is 1.2 microns, and which comprises three similar FBARs in parallel, comprising electrodes whose size is 285 microns square and a piezoelectric layer whose thickness is 1.255 microns.

Figure 6 illustrates the S parameters of a FBAR which comprises electrodes whose size is 110 microns square and a piezoelectric layer

whose thickness is 1.2 microns, and which is used as FBARs in series on a compared filter.

Figure 7 illustrates S parameters of a FBAR which comprises electrodes whose size is 110 microns square and a piezoelectric layer whose thickness is 1.255 microns, and which is used as FBARs in parallel on a compared filter.

Figure 8 illustrates a S_{21} curve of a compared filter which comprises three similar FBARs in series, comprising electrodes whose size is 110 microns square and a piezoelectric layer whose thickness is 1.2 microns, and which comprises three same FBARs in parallel, comprising electrodes whose size is 110 microns square and a piezoelectric layer whose thickness is 1.255 microns.

Figure 9 illustrates a schematic diagram of electrical equivalent circuit for a filter which comprises two FBARs in series and two FBARs in parallel.

Figure 10(a) illustrates the resonant curves of FBARs which comprises different thickness of a piezoelectric layer for FBARs in series relative to FBARs in parallel.

Figure 10(b) illustrates a S_{21} curve of a filter which comprises two types of FBARs, comprising different thickness of a piezoelectric layer, for two FBARs in series relative to two FBARs in parallel.

Figure 11(a) illustrates the resonant curves of FBARs which comprises different thickness of a piezoelectric layer and different size of electrodes for FBARs in series relative to FBARs in parallel.

Figure 11(b) illustrates a S_{21} curve of a filter which comprises two types of FBARs, comprising different thickness of a piezoelectric layer and different size of electrodes, for two FBARs in series relative to two FBARs in parallel.

According to a preferred embodiment of the invention, the filter is prepared with FBARs in series and in parallel which have different sizes of electrodes and different thicknesses of piezoelectric layer. The embodiment may be understood in view of Figures 1 and 2, which illustrate respectively a schematic diagram of the filter and a cross-section of each FBAR in the filter.

The three FBARs in series (10) are indicated in Figure 1 as are the three FBARs in parallel (11). Those six FBARs are prepared on one substrate. The FBARs in series 10 and in parallel 11 have the structure shown in Figure 2. The FBARs in series 10 and in parallel 11 comprise a top electrode 24, a bottom electrode 25, a piezoelectric layer 23 and a bridge or membrane layer 22 on a Si wafer 20 which is etched anisotropically using a backside pattern layer 21. There are two points of difference between the FBARs in series 10 and in parallel 11. One is the thickness of the piezoelectric layer 23 (shown as T in Figure 2), and the other is the size of the top electrode 24 and the bottom electrode 25 (shown as L in Figure 2).

The preparation procedure of the filter, comprising six FBARs, is described as follows. At first, silicon nitride (SiN_x) is coated at 200nm with chemical vapour deposition on both sides of a bare Si wafer 20. The SiN_x on the front side of the Si wafer 20 is a membrane layer 22. A backside pattern layer 21 is prepared on the back side of the Si wafer 20 in the SiN_x with photolithography and reactive ion etching. A bottom electrode 25 is prepared with so-called a lift-off process which is carried

out as follows. First a pattern of photoresist is prepared with photolithography. Then, chromium and gold (Cr/Au) are deposited by sputtering at thicknesses of 10nm and 100nm respectively. Cr is used as an adhesion layer. Next, the patterned photoresist and Cr/Au on it is removed with acetone, because the photoresist dissolves in acetone. After that procedure, a bottom electrode 25 is obtained. Next, Zinc Oxide (ZnO) is deposited for a piezoelectric layer 23 by sputtering. The thickness of the piezoelectric layer 23 is 1.2 microns for FBARs in series 10 and 1.255 microns for FBARs in parallel 11, respectively. In order to obtain a piezoelectric layer 23 which shows a different thickness, a photolithography and an etching are employed. The piezoelectric layer 23 is etched with acetic acid to make a contact hole 26 in order to touch a bottom electrode 25 with an electrical probe. Afterwards, a top electrode 24 is prepared by the lift-off process. The Cr and Au thickness of a top electrode 24 is set at 10nm and 100nm respectively. The top electrode 24 has a transmission line and a square working area on which one dimension shown as L in Figure2. The working area size is the same for the bottom electrode 25. When the top electrode 24 is prepared, two ground electrodes 27 are prepared as well under the same lift-off process, so the top electrode 24 has a coplanar wave-guide structure for which the characteristic impedance is set at about 50 ohms.

The size of the working area, which is equal to the centre part of the top electrode 24 and bottom electrode 25, is 110 microns square for FBARs in series 10 and 285 microns square for FBARs in parallel 11.The mask design for both electrodes is changed between FBARs in series 10 and FBARs in parallel 11.

Finally, the Si wafer 20 is etched from its backside with KOH solution, using the backside pattern layer 21 and the preparation process for the filter is finished.

A network analyser is used for the electrical measurement. At first, a measurement is carried out on each FBAR in the filter. Each FBAR, which is not connected to other FBARs, is prepared individually in order to measure the electrical response separately.

Figure 3 shows the S parameters of an FBAR in series 10, which comprises a piezoelectric layer 23 at 1.2 microns thick and a working area at L=110 microns. S_{11} is the reflection coefficient at the RF power source and S_{21} is the transmission coefficient measured at the output port. Series and parallel resonant peaks on S_{11} and S_{21} are presented at the frequency of 1.585GHz and 1.636GHz, respectively.

On the other hand, Figure 4 shows the S parameters of a FBAR in parallel 11, which comprises a piezoelectric layer 23 at 1.255 microns thick and a working area at L=285 microns. All the resonant peaks in S_{11} and S_{21} are shifted to a lower frequency relative to the same kind of peaks in Figure 3. The series resonant peak on S_{11} in Fig. 4 appears at 1.543GHz and the parallel resonant peak on S_{11} in Fig 4 and a resonant peak on S_{21} in Fig 4 are presented at 1.585GHz which is the same frequency as for the series resonant peak in Figure 3. Also, the shapes of S_{11} and S_{21} in Figure 4 are different from those in Figure 3 due to the difference of the capacitance of a working area of FBARs.

Using those two kinds of FBARs, the filter is fabricated using the configuration in Figure 1. The through coefficient (S_{21}) of the filter is shown in Figure 5. Close-in rejections of the filter appear at 1.540GHz and at 1.635GHz. One close-in rejection at 1.540GHz is due to a series resonant peak of S_{11} on FBARs in parallel 11 at 1.543GHz in Figure4. The other close-in rejection at 1.635GHz is due to a parallel resonant peak of S_{21} on FBARs in series 10 at 1.636GHz in Figure 3. An out-of-

band rejection in a frequency region below 1.540Ghz and above 1.635GHz is less than –50dB.

To compare with the preferred filter above, a filter fabricated using the same configuration in Figure1 is made. On the compared filter, FBARs for both FBARs in series 10 and FBARs in parallel 11 comprise a working area at L=110 microns. The thickness of the piezoelectric layer 23 is 1.2 microns for FBARs in series 10 and 1.255 microns for the FBARs in parallel 11.

At first, a measurement is carried out on each FBAR in the compared filter. Each FBAR, which is not connected to the other FBARs, is prepared individually in order to measure the electrical response separately.

Figure 6 shows S parameters of an FBAR in series 10, which comprises a piezoelectric layer 23 at 1.2 microns thick and a working area at L=110 microns. Since the FBAR in series 10 in the compared filter is the same as a FBAR in series 10 in the preferred filter, the S parameters in Figure 6 are the same as those in Figure 3.

On the other hand, Figure 7 shows the S parameters of an FBAR in parallel 11 in the compared filter, which comprises a piezoelectric layer 23 at 1.255 microns thick and a working area at L=110 microns. All resonant peaks on S_{11} and S_{21} in Figure 7 are shifted to lower frequency than the same kind of peaks in Figure 6. The series resonant peaks on S_{11} and S_{21} in Figure 7 appear at 1.543GHz. The parallel resonant peaks on S_{11} and S_{21} are presented at 1.585GHz which is the same frequency as for the series resonant peak in Figure 6. However, the shapes of S_{11} and S_{21} in Figure 7 are the same as those in Figure 6 because the working area is the same for both FBARs in series 10 and FBARs in parallel 11.

Using those two kinds of FBARs, the compared filter is fabricated using the configuration in Figure 1. The through coefficient (S_{21}) of the compared filter is shown in Figure 8. Close-in rejections of the compared filter appear at 1.540GHz and at 1.635GHz. Those frequencies are the same as in Figure 5. Comparing the peak depth of one close-in rejection at 1.540GHz, a close-in rejection in Figure 5 is deeper than that in Figure 7. Moreover, comparing an out-of-band rejection, the preferred filter shows less out-of-band rejection than the compared filter on which an out-of-band rejection is around –22dB in Figure 8. The superior performance of the preferred filter is obtained because of a different shape of S parameters between FBARs in series 10 and FBARs in parallel 11. The different shapes of the S parameters are due to the difference in the capacitances of the FBAR's due to their different working areas.

Comparing the preferred filter with the compared filter, the preferred filter shows a lower close-in rejection and a lower out-of-band response.

The preferred filter described above is one example for this invention. However, the thin film techniques and materials for each layer on the preferred filter described above are not restricted to those described. For example, the material for the piezoelectric layer 23 is not restricted to ZnO. Aluminium nitride (AlN) which shows a high Q value and lead titanate zirconate (PZT) which shows a large electromechanical coefficient are also usable. Also, lead scandium tantalum oxide and bismuth sodium titanium oxide are other examples of piezoelectric materials. The material for the top electrode 24 and a bottom electrode 25 is not restricted with Cr/Au. Aluminium (Al) and platinum (Pt), which are often used for electrodes, are also usable. The material for the membrane layer 22 and a backside pattern layer 21 is not restricted to SiN_x. SiO_2 is also possible.

The numbers of FBARs in series 10 and FBARs in parallel 11 are not restricted to 3 each. The numbers of FBARs in series 10 and FBARs in parallel 11 should be decided by the specifications for the level of close-in rejection, area size for the filter and so on.

The FBARs which are used as FBARs in series 10 and FBARs in parallel 11, are not restricted to an FBAR which comprises an etched hole on Si wafer 20 at the backside of a bottom electrode 25. Any air gap or a Bragg reflector may be used at the backside of the bottom electrode 25. Therefore Si wafer 20 is not necessarily used as a substrate for the FBARs.

It is sometimes usual to make electrodes larger than the working area to make a contact area of measurement probes, for instance. In this case, the working area is restricted with the area size of electrodes in contact with the piezoelectric layer 23 to form resonators where resonance occurs.